Design Concept for the Mid Infrared Instrument for NGST

Report of the Mid Infrared Steering Committee (MISC)
G. Rieke (chair); G. Wright (co-chair); F. Bortoletto, T. Greene, T. Henning, S. Kwok, P.-O. Lagage, M. Meixner, and E. Serabyn

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1. Summary

The European efforts to define the design of the mid infrared instrument for NGST need to proceed in parallel with the selection process for the United States involvement in the instrument. The Mid Infrared Steering Committee (MISC) was formed to provide essential early input from US and Canadian scientists to the design studies by ESA and by the European consortium for the instrument, so there would be a broadly supported foundation for these studies. The MISC met July 16 and 17 at Royal Observatory Edinburgh to finalize its consideration of the instrument*. Once the various aspects of the design had been fully considered, the group reached agreement by consensus on the way the design should proceed. The MISC adopted unanimously a set of recommendations that fully specify the instrument to the level of detail required for the next round of studies. These recommendations are listed at the end of this report.

* S. Kwok was unable to attend this meeting but had participated in previous discussions. The MISC chair also corresponded with Kwok previous to the meeting to be sure that his views would be accurately represented.

2. Goals for the Mid Infrared Instrument
2.1 Science Program

The mid infrared spectral region is where NGST will achieve the greatest sensitivity gain relative to any other facility. This region will therefore be central to the science that the mission can achieve.

The MISC reviewed potential applications of this dramatic advance, both updating the design reference mission developed by the NGST Project Office (through the Ad hoc Science Working Group (ASWG)) and considering other possible types of investigations. The mid infrared instrument design was considered in view of its unique contributions to the following investigations.

- *Search for the origins of galaxies*. Deep imaging will help constrain photometric redshifts and track star formation in heavily obscured galaxies at high redshift, such as the extremely red objects that are being identified with submm detections. Mid infrared spectroscopy can probe the internal dynamics of forming galaxies and the excitation mechanism in heavily obscured objects. Measurement of coronal and fine structure lines in highly redshifted active objects can probe the formation of massive black holes and the history of their accretion of matter.
- *Birth of stars and planets.* Deep imaging can find candidates for young brown dwarfs down to Jupiter-like masses. Candidates can be confirmed by spectroscopy with both the near infrared and mid infrared instruments. The initial mass function can be measured in young clusters uniformly from 0.001 to 1 solar mass. Spectroscopy can constrain models for the atmospheres of very low mass objects. Spectroscopy of the solid state features and interstellar emission lines will reveal the conditions that lead to star formation, extending even into protostellar cores, which have previously been inaccessible to detailed study. These techniques will also measure the influence of star formation on the interstellar medium.
- *Evolution of planetary systems.* Photometry and spectroscopy of Kuiper Belt objects can determine their surface composition and probe the solar debris disk and the clues it gives to the origin of our own planetary system. High contrast (coronagraphic) imaging can identify Jupiter-like planets around other stars and can probe the structures of their circumstellar disks for clues of otherwise invisible planetary systems.

2.2 Instrument Functional Requirements

To carry out these investigations, the MISC re-affirmed the list of instrument capabilities it had established and reported previously (by conference telephone meeting June 11):

For imaging:

- Wavelength range 5 - 27μm
- Diffraction limited imaging, Nyquist sampled at no longer than 8μm
- Minimum field of view 1.5 arcmin

- At least 8 spectral bands, 4-5 for SED definition, remainder for PAH isolation, brown dwarf atmosphere color identification
- Simple coronagraph
- Larger imaging field of view a goal

For spectroscopy:

- Single object, 5 - 27μm, important goal to extend to 28.3μm
- Resolution R ~ 100 from 5 to 10μm
- Resolution R ~ 1000 - 3000 from 5 to 28.3μm
- Resolution close to 3000 (or slightly higher) to be a goal

Our recommendations on high priority science objectives and instrument features to support them were determined independently of previous studies. Nonetheless, they agree excellently with other efforts. There appears to be widespread agreement within the astronomical community on the desired mid infrared capabilities for NGST.

3. Baseline Instrument Concept

3.1 Introduction

The European consortium presented a baseline instrument design, developed by the international design team which will lead the consortium work in the ESA study phase. This design concept appears to be capable of satisfying all the goals for the instrument listed above. The next step is to develop the concept to be sure it is feasible, to minimize risk and complexity in building and operating it, and to define the construction tasks.

The baseline design already includes innovations to reduce instrumental complexity, such as a plan to divide the spectrograph slit and offset it to use the two halves of the detector array to increase the spectral range. The MISC endorsed this idea and encouraged the group to conduct a proposed trade study comparing the use of two arrays instead of one in the spectrograph, since it appeared that such a design would remove a precision grating change mechanism and simplify operations. A number of additional proposals for simplification will require further evaluation during the instrument studies.

The instrument concept is described in the next section, followed by a set of recommendations by the MISC that provide specific parameters for the next step toward definition of the instrument.

3.2 Baseline Instrument Layout

The baseline instrument concept takes into account the need for a low risk, modular approach to the design and construction. Important goals were to keep the optics and internal optical interfaces between functions as simple as possible and to minimise the number of mechanisms and "switching between configurations," which would add to the calibration and operational complexity as well as power requirements and mechanical complication. In addition, where mechanisms are necessary, the consortium aimed to build on their ISO and Herschel instrument experiences, which demonstrated the importance of simple mechanisms and optical designs that provide adequate mechanism space in the layout. The result is an instrument concept in which common fore-optics feed separate modules for imaging and spectroscopy, each module with an individual array.

Having two channels in the instrument concept was found to considerably simplify the internal optical interfaces and the overall design and the complexity of mechanisms and layout. While including R ~ 100 spectroscopy in a camera via a grism is straightforward to do, it is much more complex to provide higher resolutions over a wide wavelength range requiring reflective gratings and differing pixel sizes. It is better to keep the camera as small and simple as possible. A number of camera-spectrographs (Herschel PACS and SPIRE, ESO instruments) have adopted a nominally distinct camera and spectrograph channel approach for similar reasons to the proposed NGST mid-IR concept. The two channels/two detectors concept also provides an important redundancy - e.g. not all of the mid-IR functionality would be lost in case of unanticipated damage, or should there be a component failure in one channel .

The baseline instrument concept divides the instrument functional requirements as shown in Figure 1.

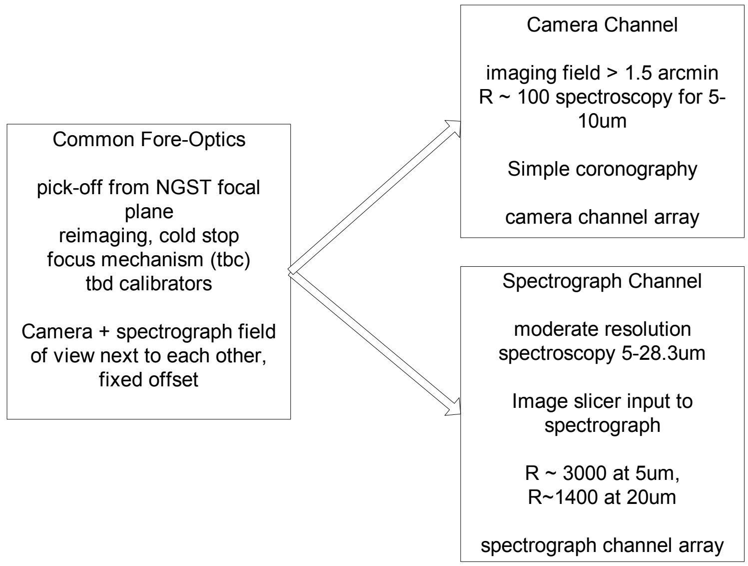

Figure 1. Basic layout for the instrument.

3.2.1 Common Fore-Optics

The common fore-optics provide a means to pick-off the light from the NGST focal plane, as required in the draft MIRI IRD, and the re-imaging system ensures that the first cold stop is early in the optical chain. Space is allowed for a focusing mechanism. It is desirable that the depth of focus of the instrument be sufficient for any expected telescope focus shifts, so the need for this mechanism will be subject to further study. The common fore-optics are a natural location for any calibration source e.g. for flat fields. Since there is no science requirement identified by the MISC for simultaneous imaging and spectroscopy of the same source, the simple approach of having the imaging and spectroscopy channel fields of view next to each other was taken.

3.2.2 Camera Channel

The baseline optical design for the camera channel together with the common fore-optics is shown in Figure 2. This camera design has a pixel scale of 0.1arcsec/pixel, and a field of view of 1.7arcmin, thus meeting the requirements set out above. The camera optics consist of three simple mirrors. Spot diagrams demonstrate excellent image quality. The distortion is also very low. The filter wheel is placed as close as possible to the detector for good thermal control and the filters are tilted to minimise ghosts.

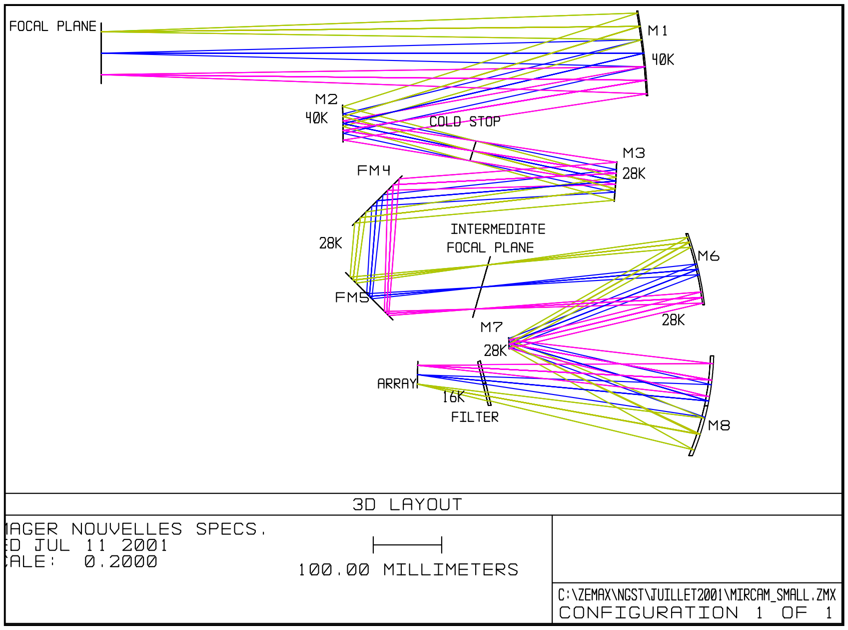

Figure 2. Design of common foreoptics (top) and camera (bottom).

Low resolution spectroscopy is provided by a slit placed at the intermediate focal plane and a grism in the filter wheel. If the slit length is very short, e.g. ~50 pixels, then it is possible for the implementation of low resolution spectroscopy to need no extra mechanisms, by placing a permanent mask for slits at the edge of the field of view. This would reduce the number of imaging pixels in one dimension by about 50, a negligible reduction in camera field.

Coronography requires a mask to be placed in the focal plane together with an associated pupil mask. The focal plane mask may share a mechanism with the slit for spectroscopy or if the spectroscopy is implemented with a permanent slit it may require a mechanism. The baseline for the coronograph is to use a classical focal plane mask. Institutes in France that are participating in the mid-IR instrument consortium have considerable expertise in developing phase-masks. Such an approach could provide considerably better rejection ($\sim10^{-6}$) than the classical mask. The feasibility of using a phase mask design will be investigated, with the goal of placing few requirements on the camera mechanisms and maintaining a simple-to-use coronograph within this camera concept.

3.2.3 Spectrograph Channel

A range of designs for the spectrograph channel was presented and discussed at the MISC meeting . These allowed the trades between complexity, resolution, cross dispersion, and division of array pixels between spectral and spatial information to be thoroughly examined. The spectrograph concept described here is one which meets the MISC recommendations set out below, as well as the instrument requirements for spectroscopy described in section 2.

The spectrograph is an integral field design with all reflective optics aside from the wavelength/order sorting filters. The input slit for the spectrograph is formed by an image slicer with 0.2arcsec/pixel and a nominal field of view of 4 x 4 arcsec. (the precise field will be determined by the detailed image slicer design, but is √(512 - space between slices) pixels on a side). The IFU optics are arranged to provide two 512 pixel long slits which are arranged above each other, and with one shifted in the dispersion direction relative to the other. As well as the physical shift of the "slit", the light for each "slit" passes through a different blocking filter. This means that the wavelength range on the top half of the array will be different from that for the lower half (cf. the shifting of wavelength with position of slit in a multi-slit MOS). This optical arrangement means that twice the wavelength range can be covered in a single exposure, and also means that tilting the grating to cover the additional wavelengths is not necessary. Figure 3 shows the wavelength ranges and orders for this concept in the case where a 1k x 2k array is used for the spectrograph channel.

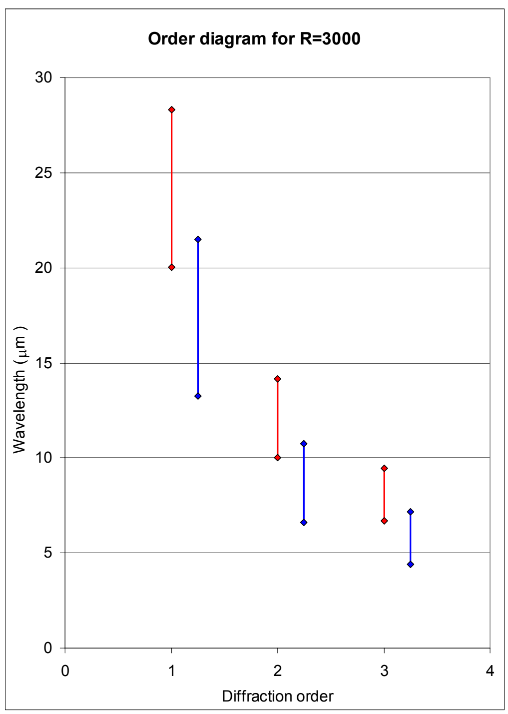

Figure 3. Strategy for obtaining a spectrum from < 5 to > 28μm using a single fixed grating. Three pairs of spectra are obtained, each with a spectrum on the top and one on the bottom half of the array.

A red and a blue spectral range are observed simultaneously. Thus in this case the filter wheel has 3 positions and 3 exposures (orders 1, 2 and 3) would be needed to cover the full band. If the concept were instead implemented using a 1k x 1k array then two gratings would be required with a total of 7 positions in the filter wheel (and 7 exposures) to cover the full band.

The grating dispersion is chosen to provide R ~3000 at 5μm, where the resolution is determined by the slit width (2-pixels). Since diffraction after the slit broadens the beam the resolution at 20μm will be ~ 1400, and at 28μm the resolution will be ~ 1000.

An optical layout for the spectrograph implemented with a 1k x1k array is shown in Figure 4.

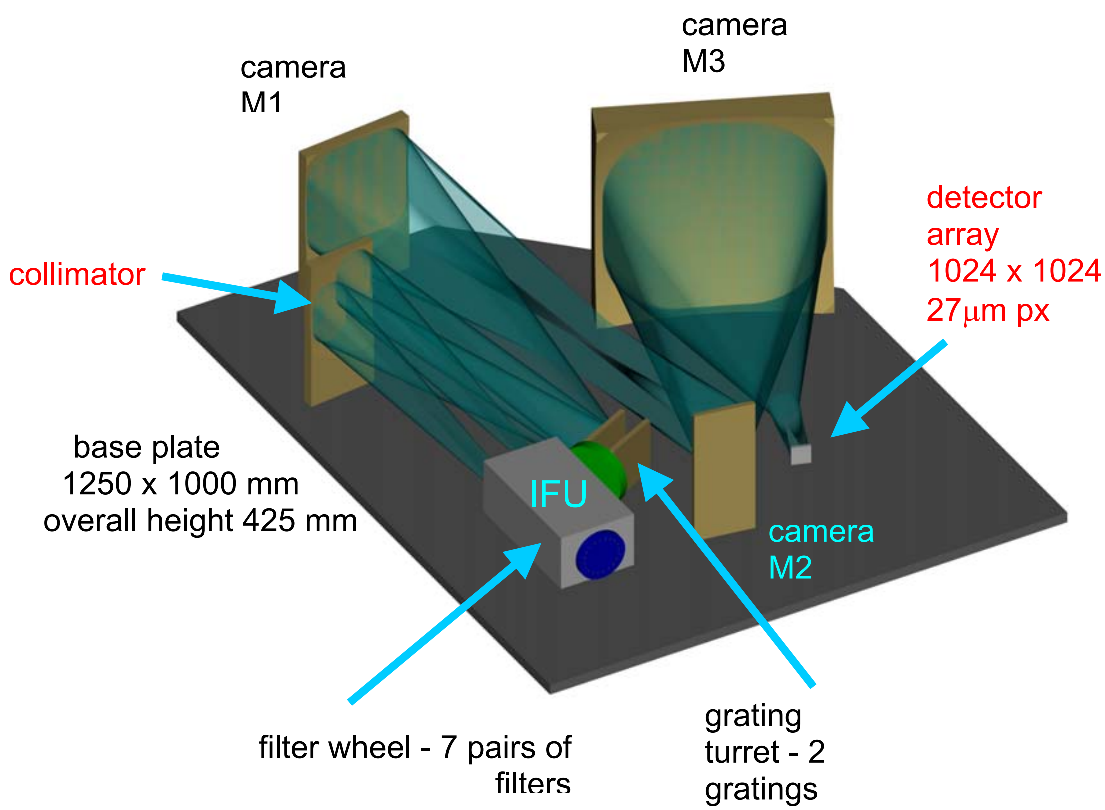

Figure 4. Layout of the spectrograph concept with a single 1k x 1k array.

The optics sizes include the oversizing of the optics to take account of diffraction in the image slicer and ensure good throughput . Spot diagrams for this optical design show good image quality at all wavelengths. The IFU design is based on that of the UIST image slicer under construction at ROE, with appropriate masks to control straylight and crosstalk, and with the two slit output described above.

4. MISC Recommendations

With regard to this instrument, the MISC reached the following unanimous recommendations. Most of them are already incorporated in the baseline concept described above.

With regard to the imaging capability of the MIR instrument concept:

1.) The projected pixel size should be 0.1 arcsec with a 1024 x 1024 array. There is no need for multiple pixel scales
2.) The instrument should be able to image sources at least as bright as 4mJy at 10μm to provide overlap with imaging from the ground. A suggestion for achieving this capability is to make use of the first read(s) of the array to obtain a measure of the signal from sources that would saturate in the full integration time. Any other approaches to increase dynamic range without increasing instrument complexity should also be considered.
3.) A minimum of 12 bandpass filters should be accommodated in the imager.
4.) The imager should include a low resolution spectroscopic capability to be used on single, compact sources. It should have R ~ 100 at 7.5μm and a slit length of at least ~ 50 pixels. As goals, this capability should be implemented without a slit changing mechanism, and with the option for two slit widths.
5.) A coronagraph operating at 5μm should be included in the instrument study. The final disposition of this capability between the mid infrared and near infrared imagers should await the results of this study, an assessment of technical developments within the consortium building the mid infrared instrument optics, and the selection of the near infrared camera team.
6.) In any case, a coronagraph operating at longer wavelengths should be included in the instrument

With regard to the spectroscopic capability of the instrument concept:

1.) The MISC endorses the proposed approach to order sorting and staggered slits to allow broader spectral range on the array and to implement spectroscopy from 5 to 28μm without a mechanism to tilt the grating.
2.) The spectrograph should use an integral field unit with a field of view of at least 2 arcsec and a goal for a field of 3 arcsec or more. The IFU should provide only one pixel scale for all wavelengths.
3.) The pixel size in the spectrograph should be 0.2 arcsec, with one or two 1024 x 1024 arrays.
4.) The instrument study should include a tradeoff between spectrograph designs using one and two arrays, with a goal to eliminate a grating exchange mechanism and to reduce the number of filter wheel positions required to obtain a full spectrum.
5.) For this trade study, the instrument spectral resolution should be > 1400 at 20μm, set as high as possible while allowing operation of the two array version with only three filter wheel positions for a full spectrum. This requirement will provide

resolution > 3000 at 5μm and ~ 3000 at 10μm. Although adjustments in resolution may be desirable as a result of the study, particularly if the single array option is selected, the basic resolution requirements indicated above should be preserved.

Important assumptions underlying these recommendations:

The array is assumed to operate at no more than 10 electrons read noise and 1 e/s dark current, imposing a requirement on its operating temperature as well as its basic performance parameters. Operation at 7K is extremely desirable, since it appears that it will reduce the dark current significantly and improve the performance of the instrument for spectroscopy between 5 and about 10μm.

Large groundbased telescopes were assumed to be able to reach one standard deviation levels of 0.4mJy or better in no longer than 30 minutes integration in broadband imaging at 10μm.

The emission of the telescope sunshade is low enough to allow operation of the instrument in 20% bandpass imaging all the way to the long wavelength cutoff of the array.

The IFU FOV goal was set in part to allow simpler operations if the telescope pointing can be improved to a 3 standard deviation upper limit of 1 arcsec radial.